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(54) **ENHANCED CONTROL OF ROAD CONSTRUCTION EQUIPMENT**

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(57) **ABSTRACT**

Novel tools and techniques for controlling road-forming machines, such as paving machines, graders, and the like. Some techniques allow a control system of a road-forming machine to transition from receiving position data from one positioning device to receiving data from another without ceasing operation and/or while limiting any resulting discontinuity in the formed road surface to within acceptable tolerances.

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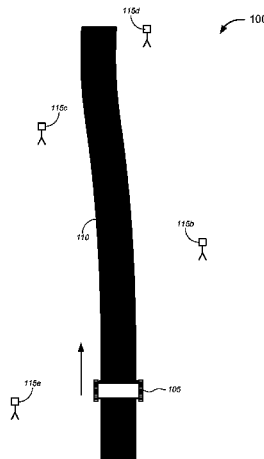
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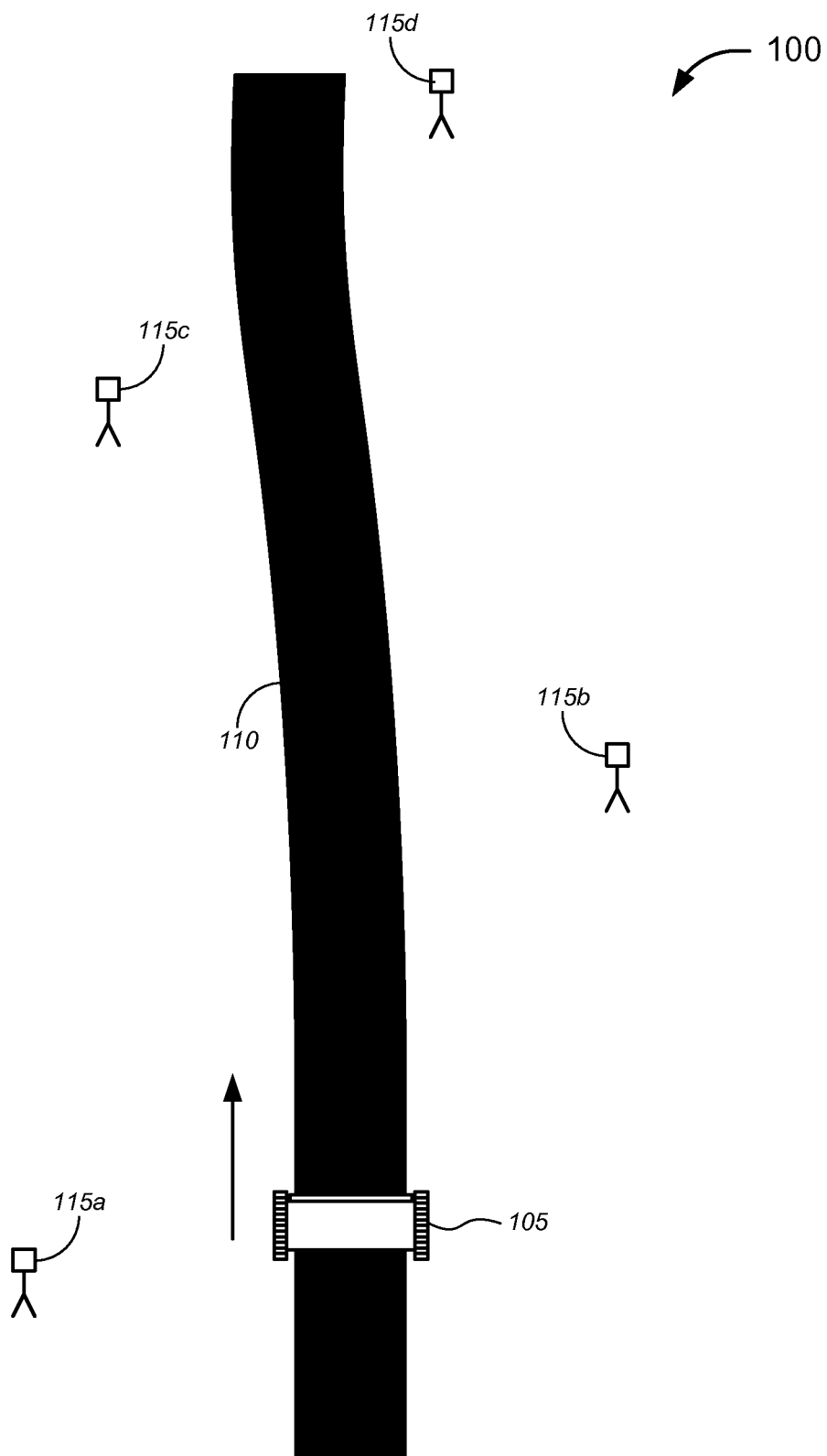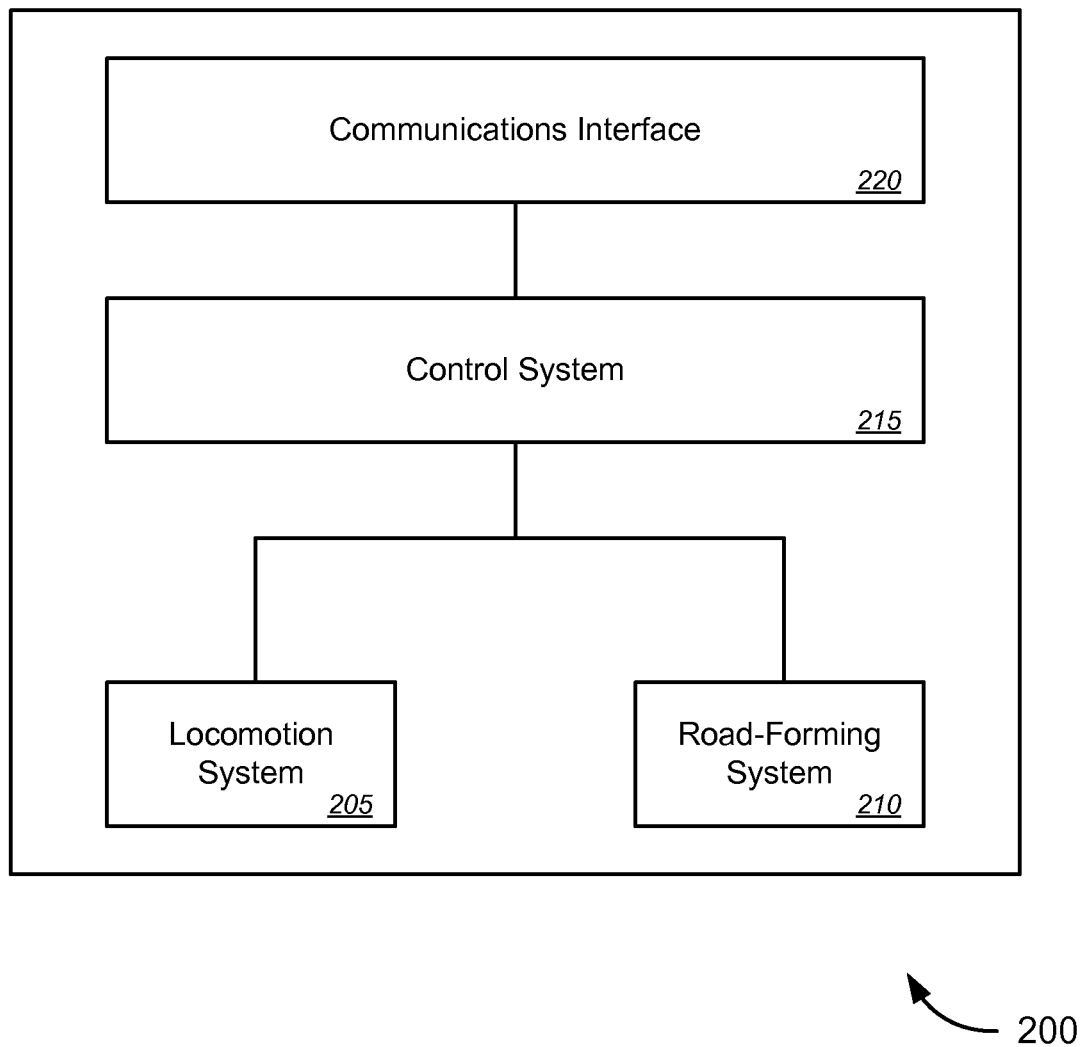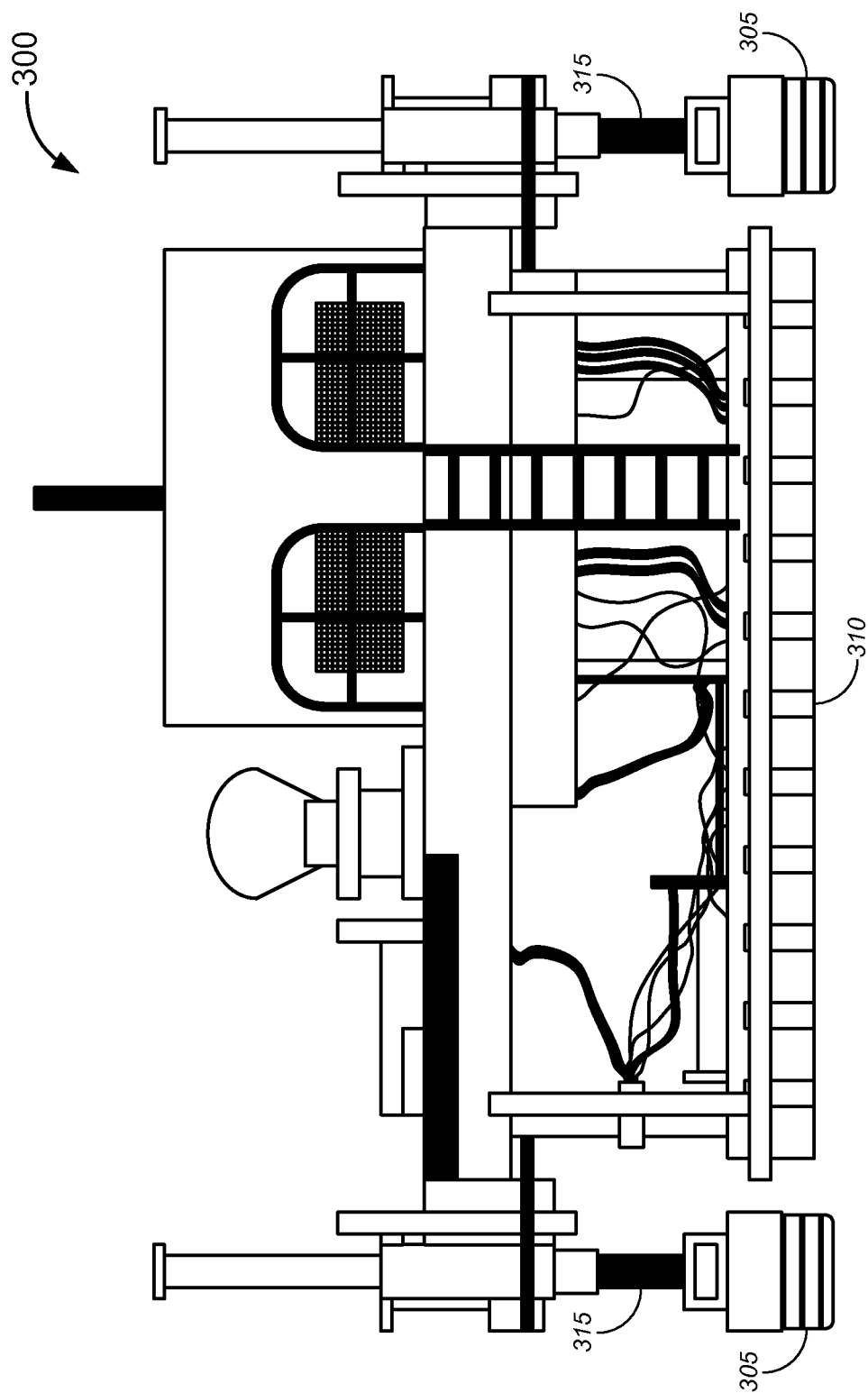
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115d

100

115c

110

115b

115a

105

Fig. 1

Fig. 2

300

315

305

310

315

305

Fig. 3

400

405

410

Fig. 4

```
        ┌─────────────────────────────┐
   505  │         Store Model         │
        └─────────────────────────────┘
                      │
                      ▼
        ┌─────────────────────────────┐
   510  │    Receive Position Data    │
        └─────────────────────────────┘
                      │
                      ▼
        ┌─────────────────────────────┐
   515  │        Select Device        │
        └─────────────────────────────┘
                      │
                      ▼
        ┌─────────────────────────────┐
   520  │      Determine Position     │◄──┐
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   525  │       Control Operation     │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   530  │     Provide User Interface  │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   535  │      Display Information     │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   540  │        Receive Input        │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   545  │        Select Device        │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   550  │   Transition Between Devices │   │
        └─────────────────────────────┘   │
                      │                    │
                      ▼                    │
        ┌─────────────────────────────┐   │
   555  │    Receive Position Data    │───┘
        └─────────────────────────────┘
```

⟋ 500

Fig. 5

605

| Processor(s) |
610

| Storage Device(s) |
625

| Input Device(s) |
615

| Output Device(s) |
620

| Communications Subsystem |
630

Working Memory

Operating System
640

645

Application(s)

635

600
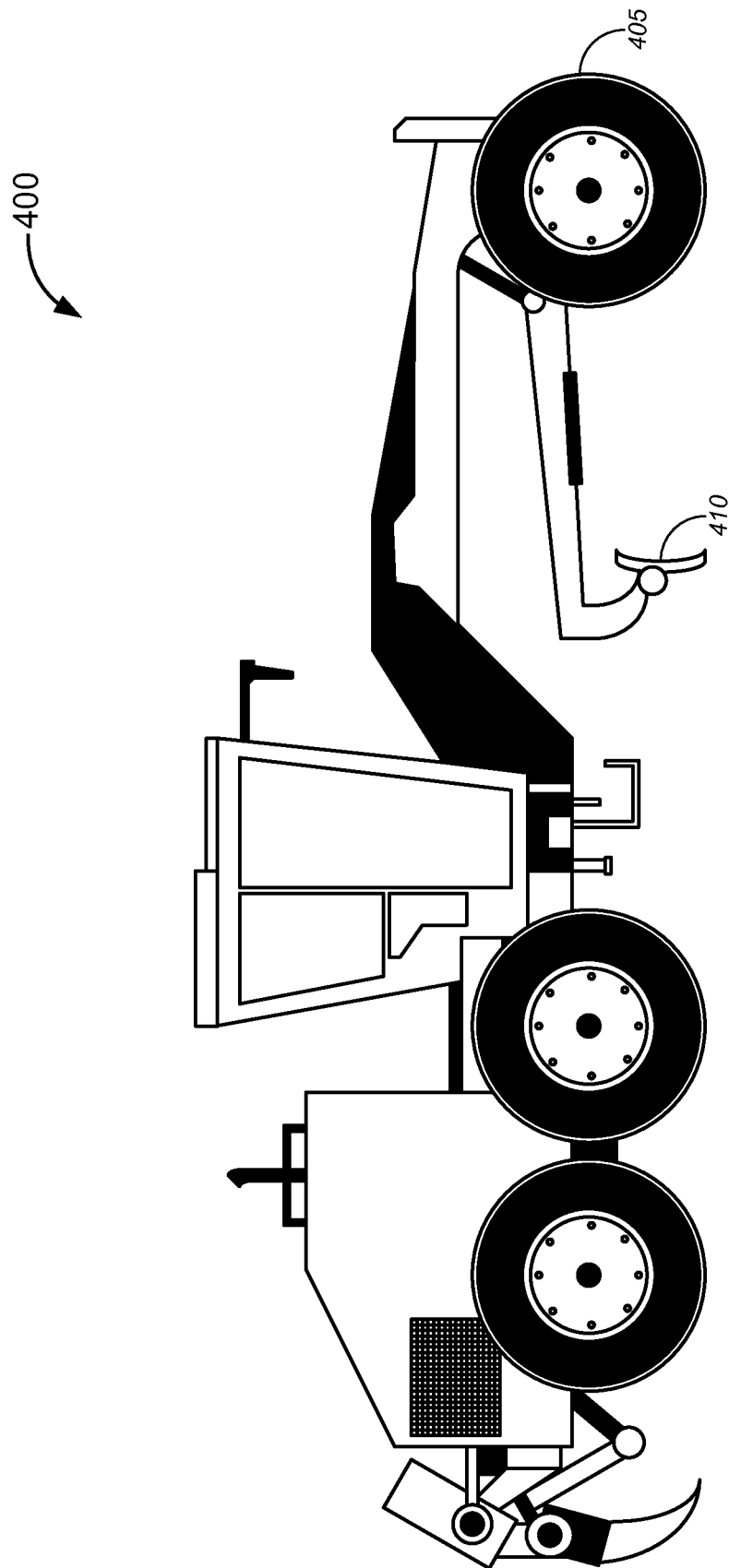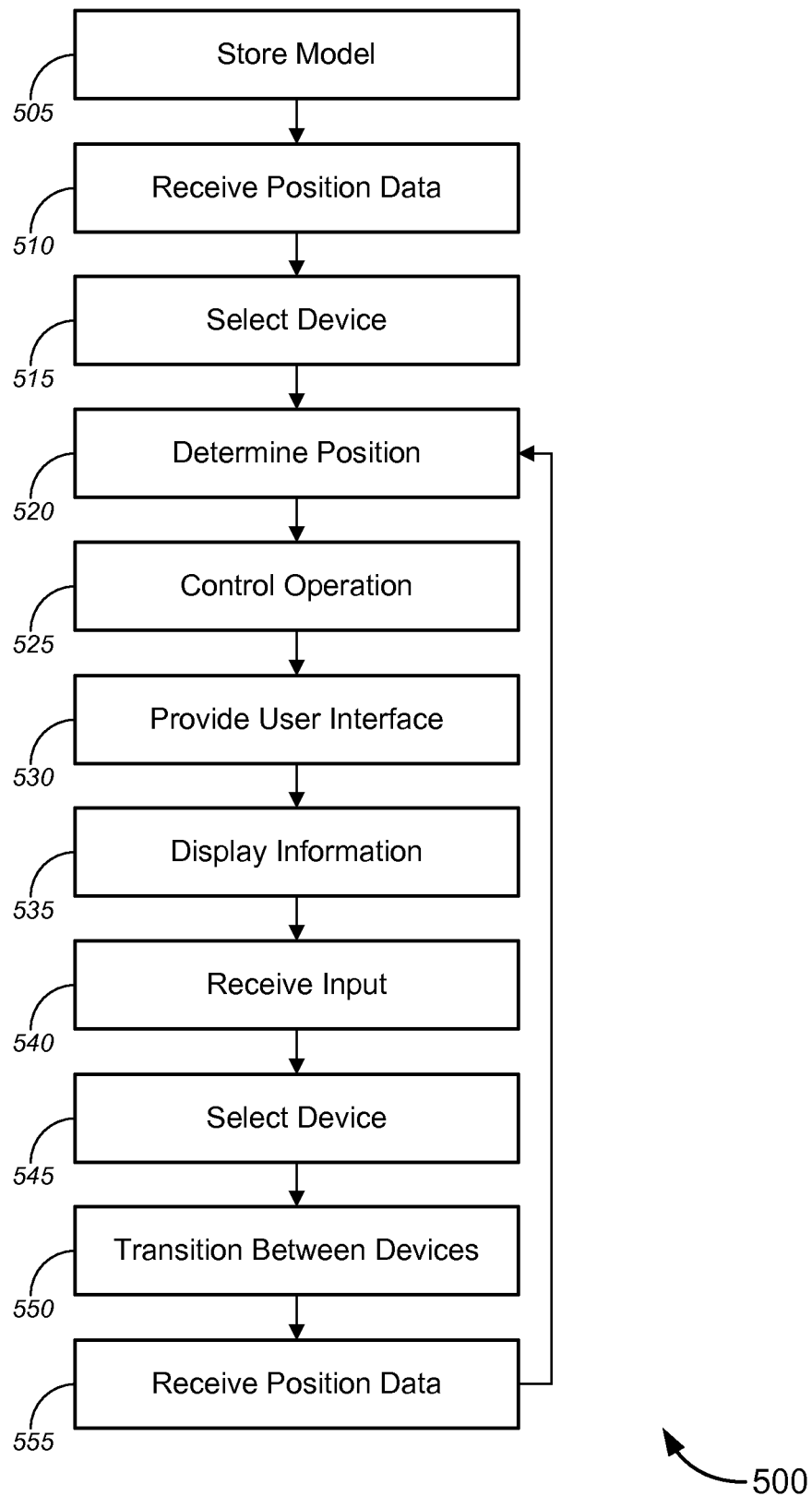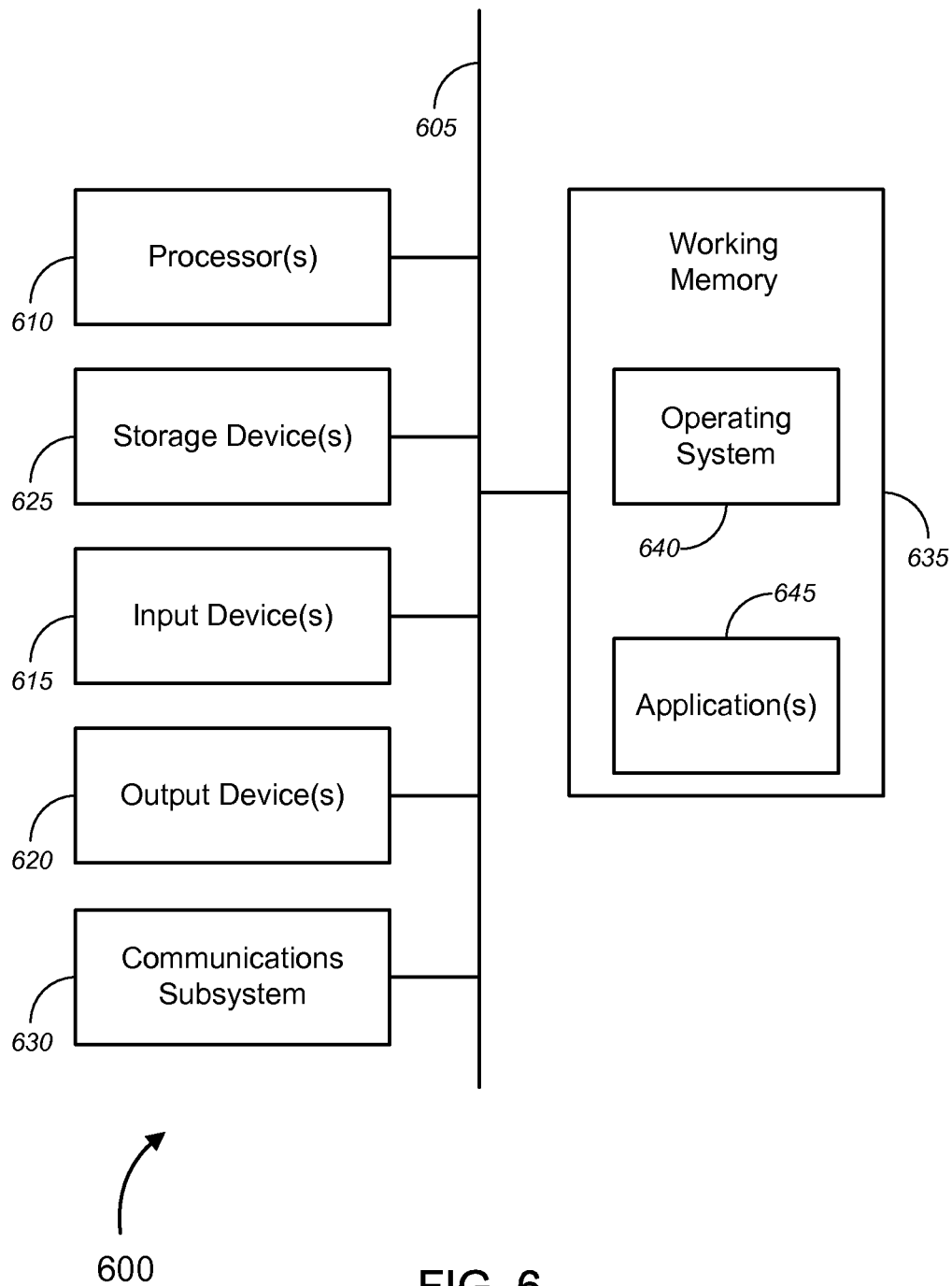
FIG. 6

ENHANCED CONTROL OF ROAD CONSTRUCTION EQUIPMENT

CROSS REFERENCE TO RELATED APPLICATION

This application may be related to U.S. application Ser. No. 14/225,702, filed on Mar. 26, 2014 by Sharp, titled "Blended Position Solutions" and assigned to Trimble Navigation, Limited (the "Blended Solutions Application"), the entire disclosure of which is incorporated by reference herein.

COPYRIGHT STATEMENT

FIELD

The present disclosure relates, in general, to road construction, and more particularly, to enhanced control systems that can employ multiple positioning devices for control of equipment.

BACKGROUND

A variety of different machines are used in the construction of roads and other infrastructure. Such machines (referred to collectively herein as "road-forming machines") can include, without limitation, equipment that displaces, shapes, and/or forms the underlying roadbed, such as earthmovers, motor graders and the like. Road-forming machines can also include machines that deposit and/or form the actual roadway material, such as asphalt pavers, which deposit asphalt on a road surface, slipform pavers, which extrude or otherwise shape concrete on a road surface, and/or the like. Such road-forming machines are commonly controlled by advanced control systems that use high-precision positioning equipment to ensure that the machines shape the earth and/or the road surface consistent with an engineer's model for the project.

In some cases, such machines might include onboard positioning equipment, such as a global navigation satellite system ("GNSS") receiver. Generally, however, such receivers do not provide the level of precision necessary for these types of projects. As a result, many such systems employ external positioning devices, such as total stations (of which many are commercially available from Trimble Navigation) to provide precise positioning information to the machine's control system. The use of such external devices, while providing precise positioning information, is not problem-free. For example, in many cases, a total station (or other positioning device) will need to be moved from one location to another, in order to continue to provide valid positioning information to the road-forming machine as the machine moves along the path of a road. Typically, the machine will have to cease operation while the positioning device is moved and calibrated at the new location. This interruption greatly reduces the efficiency of the construction operation, adding time and expense to the project. This inefficiency can be mitigated somewhat through the use of multiple positioning devices, but the inability of a control system to receive input from more than one device

simultaneously means that the machine will still have to cease operation while it transitions from one positioning device to another.

Further, every time the positioning device is moved in such projects, or a control system switches from one positioning device to another, any error in the data received from either device can introduce a discontinuity in the road surface. Such errors can result from imprecision of the calibration of positioning devices, thermal effects (which can cause minor distortion of lasers used to determine the machine's position by the positioning devices), wind and other environmental effects, and the like. Continuity of the road surface is often of primary importance (to whatever degree of precision is appropriate, depending on the step in the process). Merely by way of example, in many cases, there is a relatively large degree of freedom in variance from the model of the project, so that a road surface a few centimeters higher lower than the elevation specified by the model is acceptable. On the other hand, a discontinuity of even a centimeter in the surface of a road can create significant issues (the least of which is a severe bump for any cars that travel the road). Hence, conventional systems further degrade efficiency by requiring additional processes to prevent or remedy such discontinuities.

Accordingly, there is a need for control systems for road-forming machines that provide more robust positioning control.

BRIEF SUMMARY

Certain embodiments provide improved tools and techniques for controlling road-forming machines. In an aspect of particular embodiments, these tools allow a control system of a road-forming machine to transition from receiving position data from one positioning device to receiving data from another without ceasing operation and/or while limiting any resulting discontinuity in the formed road surface to within acceptable tolerances. The tools provided by various embodiments include, without limitation, road-forming machines, methods, computers and control systems, and/or software products. Merely by way of example, a method might comprise one or more procedures, any or all of which are executed by a computer system. Correspondingly, an embodiment might provide a computer system configured with instructions to perform one or more procedures in accordance with methods provided by various other embodiments. Similarly, a computer program might comprise a set of instructions that are executable by a computer system (and/or a processor therein) to perform such operations. In many cases, such software programs are encoded on physical, tangible and/or non-transitory computer readable media (such as, to name but a few examples, optical media, magnetic media, and/or the like).

Merely by way of example, a road-forming machine (which might be a paving machine, such as a concrete paver, asphalt paver, slip-form paver, and/or the like; milling machine; motor grader; scraper; or any other machine capable of forming a road surface and/or the earth on which a road surface will be built) in accordance with one set of embodiments might comprise a locomotion system configured to move the road-forming machine, which can include, without limitation, wheels and/or tracks, as well as the apparatus for providing power and/or steering input to such wheels and/or tracks. The road-forming machine might also comprise a road-forming system configured to form a road surface continuously as the road-forming machine moves; the road-

forming system might include, without limitation, a grader blade, a paving system, and/or the like.

In some cases, the road-forming machine might comprise a communication interface to provide communication with a plurality of position measurement devices and/or a control system comprising a processor, a non-transitory storage medium, and a set of instructions executable by the processor. Such instructions can include, without limitation, instructions to cause the road-forming machine to implement methods provided by other embodiments. Merely by way of example, in some embodiments, the set of instructions might comprise instructions to receive position data from one or more position measurement devices, including a first position measurement device and a second position measurement device. The set of instructions might further comprise instructions to control operation of the road-forming system, for example, based on determined positions of the road-forming system and a model stored on the non-transitory storage medium.

There might be further instructions to determine a first position of the road-forming system based on position data received from the first position measurement device, instructions to transition from the first position measurement device to the second position measurement device, and/or instructions to determine a second position of the road-forming system based on position data received from the second position measurement device. In some cases, the transition from the first position measurement device to the second position measurement device can be accomplished without interrupting movement of the road-forming machine or formation of the road surface and/or without introducing a discontinuity in the formed road surface greater than a specified threshold value.

Another set of embodiments provides computer systems, including without limitation control systems for road-forming machines. One exemplary control system might comprise one or more processors and a non-transitory computer readable medium in communication with the one or more processors. A further set of embodiments provides apparatus, which can include without limitation, a non-transitory computer readable medium having encoded thereon instructions for programming such a control system. In either case, the computer readable medium having encoded thereon a set of instructions executable by the computer system to perform one or more operations, including without limitation operations consistent with methods provided by various embodiments.

An exemplary set of instructions might comprise instructions to receive position data from two or more position measurement devices, including a first position measurement device and a second position measurement device. The set of instructions could further include instructions to control operation of a locomotion system of the road-forming machine and a road-forming system of the road-forming machine to form a road surface continuously, e.g., based on determined positions of the road-forming system and a model stored on the non-transitory computer readable medium. The set of instructions might also include instructions to determine a first position of the road-forming system based on position data received from the first position measurement device, instructions to transition from the first position measurement device to the second position measurement device, and/or instructions to determine a second position of the road-forming system based on position data received from the second position measurement device. In some cases, this transition can be performed without interrupting movement of the road-forming machine or formation of the road surface,

and/or without introducing a discontinuity in the road surface greater than a specified threshold value.

Yet another set of embodiments provides methods. One exemplary method might comprise forming a road surface with a road-forming machine, such as those described herein. Merely by way of example, a road-forming machine might comprise a locomotion system configured to move the road-forming machine, a road-forming system configured to form a road surface continually as the road-forming machine moves, a communication interface to provide communication with a plurality of position measurement devices, and/or a control system configured to control operation of the road-forming machine.

The method, then, might comprise receiving, e.g., with the control system, position data from two or more position measurement devices, including a first position measurement device and a second position measurement device. In some cases, the method further comprises controlling, with the control system, operation of the locomotion system and the road-forming system, for example, based on determined positions of the road-forming system and a model stored on the non-transitory storage medium. In particular embodiments, the method can include determining, with the control system, a first position of the road-forming system based on position data received from the first position measurement device; transitioning, with the control system, from the first position measurement device to the second position measurement device; and/or determining a second position of the road-forming system based on position data received from the second position measurement device. In a particular aspect, the transitioning operation can occur without interrupting movement of the road-forming machine or formation of the road surface and without introducing a discontinuity in the formed road surface greater than a specified threshold value.

BRIEF DESCRIPTION OF THE DRAWINGS

A further understanding of the nature and advantages of particular embodiments may be realized by reference to the remaining portions of the specification and the drawings, in which like reference numerals are used to refer to similar components. In some instances, a sub-label is associated with a reference numeral to denote one of multiple similar components. When reference is made to a reference numeral without specification to an existing sub-label, it is intended to refer to all such multiple similar components.

FIG. 1 illustrates a system for providing positioning information to a road-forming machine, in accordance with various embodiments.

FIG. 2 is a simplified block diagram illustrating a generic road-forming machine, in accordance with various embodiments.

FIG. 3 illustrates a paving machine, in accordance with various embodiments.

FIG. 4 illustrates a motor grader, in accordance with various embodiments.

FIG. 5 is a process flow diagram illustrating a method of controlling a road-forming machine, in accordance with various embodiments.

FIG. 6 is a generalized schematic diagram illustrating a computer system, in accordance with various embodiments.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

While various aspects and features of certain embodiments have been summarized above, the following detailed descrip-

tion illustrates a few exemplary embodiments in further detail to enable one of skill in the art to practice such embodiments. The described examples are provided for illustrative purposes and are not intended to limit the scope of the invention.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the described embodiments. It will be apparent to one skilled in the art, however, that other embodiments of the present may be practiced without some of these specific details. In other instances, certain structures and devices are shown in block diagram form. Several embodiments are described herein, and while various features are ascribed to different embodiments, it should be appreciated that the features described with respect to one embodiment may be incorporated with other embodiments as well. By the same token, however, no single feature or features of any described embodiment should be considered essential to every embodiment of the invention, as other embodiments of the invention may omit such features.

Unless otherwise indicated, all numbers used herein to express quantities, dimensions, and so forth used should be understood as being modified in all instances by the term "about." In this application, the use of the singular includes the plural unless specifically stated otherwise, and use of the terms "and" and "or" means "and/or" unless otherwise indicated. Moreover, the use of the term "including," as well as other forms, such as "includes" and "included," should be considered non-exclusive. Also, terms such as "element" or "component" encompass both elements and components comprising one unit and elements and components that comprise more than one unit, unless specifically stated otherwise.

Certain embodiments provide improved tools and techniques for controlling road-forming machines. In an aspect of particular embodiments, these tools allow a control system of a road-forming machine to transition from one positioning device to another without ceasing operation and while limiting any resulting discontinuity to within acceptable tolerances. For example, FIG. 1 (which is not drawn to scale) illustrates a system **100** for providing position information to a road-forming machine **105**. As noted above, such road-forming machines **105** can include any number of machines or vehicles, such as, without limitation, equipment that displaces, shapes, and/or forms the underlying roadbed, such as earthmovers, milling machines, motor graders, and the like, as well as machines that deposit and/or form the actual roadway material, such as asphalt pavers, which deposit asphalt on a road surface, concrete pavers, slipform pavers, which extrude or otherwise shape concrete on a road surface, and/or the like. In the example illustrated by FIG. 1, the road-forming machine **105** might be an asphalt paver that deposits asphalt on an existing surface of a road **110** to improve that surface.

Typically, most road-forming operations (whether creating the underbed or applying the road surface) are designed using advanced modeling software, such as the Trimble Office™ package commercially available from Trimble Navigation Ltd. Using such software, an engineer can create a model for the road that accounts for the topography of the area, any technical or regulatory constraints (such as maximum allowable grade, and the like), and any other design features of the project. Such models generally are oriented to a local or (more likely) global coordinate system, such as latitude/longitude/elevation. The road **110**, then, is formed consistently with this model, to whatever degree of precision is required.

To ensure consistency between the formed road **110** and the design model, the location of the road-forming machine **105** relative to the coordinate system in use must be carefully

managed. There are several techniques for managing the location of the machine **105**. For example, the control system of the machine **105** itself might include a global navigation satellite system ("GNSS") receiver. Generally, however, an onboard GNSS receiver does not provide the precision necessary to conform sufficiently to the established model for the road **110**. Accordingly, an accepted practice is to track the position of the machine **105** with one or more high-precision position measurement devices **115** (also referred to herein as "positioning devices"). Such position measurement devices **115** can include, without limitation, total stations such as those available from Trimble Navigation Ltd., rovers such as those disclosed in U.S. Pre Grant Pub. No. 2012-0166137-A1, the descriptions of which are incorporated herein by reference, or any other device capable of providing an external reference of the machine's **105** position. Such a position measurement device, e.g., **115a**, after determining the position of the machine **105** (through whatever technique) can then communicate that position information to the control system of the machine **105**.

A variety of techniques are available for a position measurement device **115** to communicate position information to the machine **105**. In some cases, standard communication interfaces, such as IEEE 802.11x (WiFi) radios or cellular radios, might be installed in the position measurement device **115** and the control system of the machine **105**. In other cases, proprietary single- or multi-channel radios might provide such communication. In any case, the position measurement device **115** provides position information to a control system (which might be located, but need not necessarily be located on the machine **105**), which determines the position of the machine **105** based on the position information received from a position measurement device, such as device **115a**.

As the machine **105** moves along the road, however, the position solution provided by a particular position measurement device **115a** might degrade, because of the distance between the machine **105** and the device **115a**, obscured sightlines between the machine **105** and the device **115a**, or various other factors. Accordingly, the machine will need to obtain position information from a different position measurement device, e.g., **115b** (which can be a different device from the device **115a** or can be the same device moved to a different station). This process can continue, using devices **115c** and **115d** in sequence as the machine moves down the road **110**. In a particular aspect, two (or more) devices might be used in a leapfrog fashion, such that a single position measurement device might serve as device **115a** and device **115c**, while another position measurement device might as device **115b** and device **115d**.

Conventionally, the transition from obtaining position information from one device **115** to obtaining position information from another device **115** (or from the same device **115** at a different station) requires the machine **105** to be stopped and recalibrated. Further, because of minor error in the position solutions provided by one or the other (or both) of the devices **115**, the calculated position of the machine **105** might experience a discontinuity during the transition. As noted above, both the need to cease operations and the potential for discontinuity can present problems for the project. Various embodiments, as described in further detail below, can avoid these problems by allowing the machine **105** to transition from one position measurement device (e.g., **115a**) to another device (e.g., **115b**) without ceasing operation and while maintaining continuity (to within a specified precision) in the calculation of the position of the machine **105**.

FIG. **2** is a simplified block diagram illustrating a generic road-forming machine **200**, in accordance with various

embodiments. (It should be noted that, although the description herein generally refers to road-forming machines, embodiments are not so limited, and various embodiments can be used to control any type of vehicle, in including in particular heavy equipment vehicles, which include road-forming machines and other construction equipment, tractors, heavy-duty trucks, and the like.) The generic road-forming machine can represent any suitable type of machine, including without limitation those described above, as well as the specific (but not limiting) examples depicted in FIGS. **3** and **4**. The generic machine **200** comprises a locomotion system **205**. The locomotion system **205** can include any components that provide movement for the machine **200**, including without limitation engine, drivetrain, suspension, wheels, tracks (or other ground-contact components), steering systems and components, braking systems and components, and/or the like. The machine **200** might further comprise a road-forming system **210**, which can include any of a variety of tools or components designed to form, shape, move, extrude, compact or otherwise manipulate a ground surface, such as a dirt underbed for a road, a paving material (e.g., concrete, asphalt, etc.).

In an aspect, the machine **200** further comprises a control system **215**, which can comprise a special-purpose computer or a programmed general-purpose computer (general examples of which are described below with regard to FIG. **6**). The control system **215** communicates with various systems of the machine **200** (including without limitation those described above) and controls the operation of the machine **200**, including without limitation the operation of the locomotion system **205** and the road-forming system **210**. As noted above, the locomotion system **205** and the road-forming system **210** each can include a variety of components, and the skilled reader should appreciate that and/or each system **205**, **210** can perform one or more functions; for instance, the locomotion system **205** perform steering functions, horizontal and/or vertical movement functions, and the like. As used herein, the term "control" (and its derivatives), when applied to controlling such systems, means providing control input for one or more functions performed by one or more components of such a system. Thus, for example, when controlling the locomotion system **205**, the control system **215** might provide control input to the locomotion system **205** with regard to forward velocity of the machine **205** based on the techniques described herein, but might not provide control input for a steering function (which might be controlled by an operator), or vice versa.

In some respects, the control system **215** operates in response to operator input, while in other respects, the control system **215** provides automated control over machine **200** operations. In particular embodiments, for example, the control system **215** can be loaded with a design model for the project and can operate the machine **200**, largely autonomously, to conform with the design model. In other cases, the control system **215** might involve more user interaction; for example, the control system might accept user input to modify parameters specified by the model to account for site-specific conditions or events, and/or the control system, rather that providing autonomous control over other machine **200** systems, might provide guidance to an operator who manually controls such systems.

The machine **220** can also include a communications interface **220**, which might be integrated with the control system **215** or otherwise in communication with the control system **215**. The communication interface **220** can include any hardware or software necessary to provide communication between the control system **215** and external devices, such as

ports for wired communication (e.g., serial ports, Ethernet ports), wireless radios (e.g., Bluetooth™ radios, 802.11x radios, cellular radios and other standard or proprietary radio frequency (RF) communication radios). In an aspect, the communication interface **220** provides connectivity between the machine **200** (or more precisely, the control system **215**) and various data sources, including office computers and field computers (which can be used to upload the project design model to the control system **215**) and position-measurement devices, from which the control system **215** can receive position data (e.g., as described in further detail below) to ensure that the as-built project remains consistent with the design model.

It should be appreciated that the machine **200** depicted in FIG. **2** is illustrated, and described, with a high degree of generality, and that a typical road-forming machine will have many other components and systems. The machine **200** is described herein merely for purposes of illustrating the concepts of certain embodiments with regard to controlling a wide variety of road-forming machines, which necessarily will feature different types of systems and components to accomplish various road-forming tasks.

For instance, FIG. **3** illustrates a paving machine **300**, in accordance with various embodiments, which can be considered one specific type of road-forming machine, which can form a road surface by depositing and/or extruding paving material to form a road surface. The paving machine **300** might be a slipform paver (or "white paver") that extrudes concrete provided by separate vehicles, or it might be an asphalt paver that deposits asphalt from a hopper on the machine **300** itself. In either case, the paving machine might have a locomotion system that comprises a set of tracks **305**, which provide locomotion of the machine **300**. The paving machine **300** might also comprise a communication interface and/or a control system which are (not illustrated on FIG. **3** but described above with respect to FIG. **2**). The control system, for example, can control operation of the locomotion system (including the tracks), for example, by controlling a speed of the tracks and/or steering of the machine through the tracks, in accordance with the techniques described in further detail below.

Additionally, the paving machine **300** might comprise a paving system, which can include apparatus **310** for depositing, extruding, and/or otherwise forming a paving material on a road surface, as well as a set of legs **315** that control a height of the apparatus **310** from the ground surface on which the tracks **305** are situated. The control system can control various aspects of this paving system, for example to set an elevation of the top surface of the paving material, to control the speed at which paving operations are performed, and/or the like.

FIG. **4** illustrates a motor grader **400**, in accordance with various embodiments, which can be considered another example of a road-forming machine, and which can form a road surface, e.g., by removing and/or moving material to form an underbed of the road surface, and/or by moving and/or removing material from the road surface itself. Like the paving machine described above (and all road-forming machines more generally), the motor grader **400** can include a control system and/or a communication interface (not illustrated on FIG. **4**), which can function as described above with regard to FIG. **2**. The motor grader **400** might also include a locomotion system, which can include wheels **400**, as well as an engine, drivetrain, steering system, and/or the like, as well as a road-forming system, which in this case can include a scraper blade **410** and apparatus for orienting the scraper

blade **410**. Both the locomotion system and the road-forming system can be controlled by the control system, as described above with respect to FIG. **2**.

Although FIG. **2** illustrates a road-forming machine in general, and FIGS. **3** and **4** illustrate specific examples of such machines, the skilled reader should understand that embodiments are not limited to these specific examples. Rather, embodiments can include any type of road-forming machine (or any type of machine more generally) that can operate in accordance with the techniques and principles described herein. For example, FIG. **5** illustrates a method **500** of controlling a road-forming machine in accordance with one set of embodiments. While the techniques and procedures of FIG. **5** are depicted and/or described in a certain order for purposes of illustration, it should be appreciated that certain procedures may be reordered and/or omitted within the scope of various embodiments. Moreover, while the method illustrated by FIG. **5** can be implemented by (and, in some cases, are described below with respect to) the systems (including without limitation control systems) and machines illustrated by FIGS. **1-4** (or components thereof), these methods may also be implemented using any suitable hardware implementation. Similarly, while the systems of FIGS. **1-4** (and/or components thereof) can operate according to the methods illustrated by FIG. **1** (e.g., by executing instructions embodied on a computer readable medium), the systems can also operate according to other modes of operation and/or perform other suitable procedures.

The method **500** of FIG. **5** might comprise storing, e.g., in a control system, a design model for a road-forming project (block **505**). As noted above, such a model may be created by an office computer, or another appropriate device, and transmitted or otherwise uploaded to the control system of a road-forming machine. (Alternatively, in some embodiments, the control system itself might be used to create or update a design model.) In an aspect, a design model can specify dimensions and positions of project features. Merely by way of example, with regard to a road, the design model might specify latitude and longitude coordinates for edges of the road and an elevation of the crown and/or the edges of the road, with coordinates provided for various points (spaced as frequently as necessary) along the length of the road. Such a model can be stored on a computer readable medium (e.g., by a control system or other device) and can serve as a reference against which the project or a project feature (e.g., a road) is built.

The skilled reader can appreciate that, in order to maintain fidelity to the model, the road-forming machine must maintain an awareness of the position of whatever road-forming system it includes (which generally is a function of the position of a reference point on the machine itself, such as the position of an optical target, a GPS receiver, and/or the like), so that the formed road surface (or under bed, etc.) dimensionally and positionally satisfies the constraints imposed by the model. As noted above, in some cases, the road-forming machine can determine its own position using onboard facilities, but this technique often does not provide sufficient accuracy and/or precision.

Hence, the method **500** can further include receiving (e.g., with a control system of a road-forming machine or other vehicle) position data from two or more position measurement devices (block **510**). In some cases, the method **500** will include selecting one of the position measurement devices from which to receive position data and/or to use the received position data (block **515**). A variety of techniques can be used

to select which position measurement device's data should be used by the control system, as described in further detail below.

The method **500**, then, can include determining, at block **520**, a first position of the road-forming machine (and/or the road-forming system thereof). In an aspect of some embodiments, such a determination is made based on the position data received from the selected position measurement device. For instance, a particular embodiment, the position measurement device might transmit to the control system a measured position of an optical target (or other reference point) on the road-forming machine, and the control system might be programmed with instructions to derive a position of one or more points of interest on the machine (such as positions, in 3 dimensions, of each endpoint of a bottom surface of a motor grader blade, of each lateral endpoint of an extrusion system or pavement deposition system, and/or the like). Such points of interest might each have a known offset from the reference point, and, as such, the position of each such point can be known in relation to the reference point. Hence, in determining the position of the road-forming machine, the control system might actually determine the position of one or more such points of interest relative to the position of the machine and/or a reference point thereon.

In some embodiments, the method **500** can further comprise controlling operation of the road-forming machine and/or various systems thereof (block **525**). More particularly, in some embodiments, the method can include controlling operation of a locomotion system and/or a road-forming system, based on a comparison of positions of the road-forming machine (and/or various points of interest thereof, as described above) with reference points specified by the design model. This comparison can occur continuously and/or periodically (on whatever frequency is appropriate to attain the desired precision of fidelity to the model), and the operation of various systems can be adjusted based on this comparison.

Merely by way of example, in the context of a paving machine, if the model indicates that the road surface should curve beginning at a certain point, when the machine (or more particularly the paving system thereof) reaches that point, the control system might adjust steering of the tracks of the paving machine to produce the curve specified by the model. Similarly, the paving machine might adjust the height of one of more legs that support the paving system to ensure that the formed road surface conforms to an elevation specified by the model at the latitude/longitude coordinates that the control system has determined to be the position of the paving system a given point in time. To use another example, the steering apparatus, wheel speed, and/or blade position/orientation of a motor grader can be controlled by control system to ensure consistency of a graded surface to a model of that surface.

The control system might receive various forms of input and provide various forms of output, other than merely receiving position data and providing control output. For example, the control system might receive user input and/or provide output to a user. Accordingly, in some cases, the method **500** includes providing a user interface to provide for such user interaction (block **530**). For example, the user interface can be used to output information for a user, e.g., by displaying the information on a display device, printing information with a printer, playing audio through a speaker, etc.; the user interface can also function to receive input from a user, e.g., using standard input devices such as mice and other pointing devices, motion capture devices, touchpads and/or touchscreens, keyboards (e.g., numeric and/or alphabetic), microphones, etc. In some cases, the user interface might be

provided in a cab of the road-forming machine. In other cases, the control system might communicate with a remote device (such as a field computer), and the user interface might be implemented by such a remote device. In any case, the user interface can provide for various types of user interaction.

Merely by way of example, the method **500** can include displaying information with the user interface (block **535**). Such information can include a variety of different types of data with regard to the operation and or control of the road-forming machine. For instance, the user interface might display information about operational parameters of the machine and/or the systems thereof, information about the design model and/or the machine's progress in implementing the model.

In a particular aspect, the user interface can display information about any position measurement devices with which the control system can communicate and/or from which the control system can receive position data. Such information can include, without limitation, a distance to each of the position measurement devices from the current position of the machine, information about the location of each of the position measurement devices (which could be presented graphically, e.g., as a map showing the identified position measurement devices and the road-forming machine, and/or texturally, e.g., as positions of each position measurement device expressed in relation to the coordinate system used for the project, such as latitude/longitude/elevation). Such information can also include an identification of which position measurement device(s) currently provide the position data that is being used to determine the position of the machine at that time.

Similarly, the method **500** might comprise receiving input (e.g., at the control system) with the user interface (block **540**). Such input can include control input for operation of the road-forming machine, and/or various systems thereof, such as input to begin road-forming operations, to cease road-forming operations, to power up or power down the road-forming machine, to provide manual modification of the steering of wheels or tracks, to provide manual control over a height of one or more legs supporting a paving system, to manually control a position of a motor grader blade, and/or to otherwise provide manual operational control of the machine or any of its systems. Further, as noted below, the control system may be programmed to ensure that the formed road surface has no discontinuities greater than a particular tolerance, and the user interface can receive user input to define such tolerances. For example, the control system might ensure that any such discontinuities do not exceed a vertical and/or horizontal threshold value, the control system might receive user input specifying vertical and/or horizontal threshold values and/or an overall threshold value that should not be exceeded in this regard. As another example of a threshold, the control system might have defined a minimum (or maximum) distance threshold over which discontinuities should be resolved. For instance, a distance threshold could specify the linear distance over which any discontinuity (vertical or horizontal) is absorbed to mitigate surface or alignment discrepancies.

In a particular embodiment, the user-interface can receive user input to specify which position measurement device (of a plurality of identified position measurement devices) should be used by the control system to determine the position of the road-forming machine. Merely by way of example, as noted above, identified position measurement devices can be shown in a list, on a map, and/or the like, with associated information (such as location of each device, the distance from the machine of each device, a signal strength of the

signal received by the control system from each device, etc.). The control system may be configured to allow the user to select any such position measurement device as the device to be used to determine the position of the road-forming machine, e.g., by touching an identification of one of the position measurement devices on a touchscreen, scrolling through a list of devices with the cursor, selecting one of the devices with a mouse, and/or the like.

In an aspect, the method **500** might include selecting a new position measurement device (of the plurality of such devices) from which to receive position data (block **545**). The control system might use one or more of any of a variety of techniques to select the new position measurement device from which to receive data to determine the position of the machine. Merely by way of example, the control system might merely select a position measurement device that has been specified by user input (e.g., as described above).

Alternatively and/or additionally, the control system might automatically (i.e., without user input) select a new position measurement device based on any of a number of factors. For instance, the control system might select the closest position measurement device, the position measurement device with the strongest signal, and/or the like. In some cases, the control system might take into account the movement of the machine and/or details of the design model to select a new position measurement device. For instance, the control system might select the closest position measurement device in the direction in which the machine is currently traveling, the closest position measurement device to a future position of the machine (as specified by the model), and/or the like. Based on the disclosure herein, the skilled reader will appreciate that the control system could use any of a variety of different decision matrices or algorithms to select a new position measurement device.

The method **500**, then, can also include transitioning from the original position measurement device to the selected position measurement device (block **535**). In other words, the control system might switch from using data from the original position measurement device to determine the machine's position to using data from the newly-selected position measurement device to determine the machine's position. Once the transition to the selected position measurement device has been performed, the method **500** can include, at block **555**, receiving position data from the selected position measurement device (as described above, for example) and can continue from block **520** with determining the position of the machine or vehicle.

As noted above, a novel aspect of some embodiments is the ability to transition from one position measurement device without affecting operation of the road-forming machine. Hence, in some cases, the transition and/or position determination using data from a new position measurement device can be performed without interrupting movement of the road-forming machine or formation of the road surface. Alternatively and/or additionally, this continuous performance of road-forming operations can be accomplished without introducing a discontinuity in the formed road surface greater than a specified threshold value (which might be specified, as noted above, through user input, or which might be specified by the model itself, by default parameters in the control system, and/or the like).

To accomplish such a transition without affecting operations, the control system might use any of a variety of techniques to allow for a smooth transition. Merely by way of example, the control system, for some period of time (or while the machine travels some distance) might receive position data from the original position measurement device and

the new position measurement device and/or might determine a blended position solution based on some combination of the data from both devices, in order to minimize any discontinuities in the position solution based on differential error between the position data provided by each respective position measurement device. The Blended Solutions Application, already incorporated herein by reference, describes several techniques (any of which can be employed with the method **500**) to determine a blended position solution for the position of the machine at a given point in time.

FIG. **6** provides a schematic illustration of one embodiment of a computer system **600** that can perform the methods provided by various other embodiments, as described herein, and/or can function as a control system for a road-forming machine or other vehicle, an office computer, a field computer, a control system for a position measurement device, and/or the like. It should be noted that FIG. **6** is meant only to provide a generalized illustration of various components, of which one or more (or none) of each may be utilized as appropriate. FIG. **6**, therefore, broadly illustrates how individual system elements may be implemented in a relatively separated or relatively more integrated manner.

The computer system **600** is shown comprising hardware elements that can be electrically coupled via a bus **605** (or may otherwise be in communication, as appropriate). The hardware elements may include one or more processors **610**, including without limitation one or more general-purpose processors and/or one or more special-purpose processors (such as digital signal processing chips, graphics acceleration processors, and/or the like); one or more input devices **615**, which can include without limitation a mouse, a keyboard and/or the like; and one or more output devices **620**, which can include without limitation a display device, a printer and/or the like.

The computer system **600** may further include (and/or be in communication with) one or more storage devices **625**, which can comprise, without limitation, local and/or network accessible storage, and/or can include, without limitation, a disk drive, a drive array, an optical storage device, solid-state storage device such as a random access memory ("RAM") and/or a read-only memory ("ROM"), which can be programmable, flash-updateable and/or the like. Such storage devices may be configured to implement any appropriate data stores, including without limitation, various file systems, database structures, and/or the like.

The computer system **600** might also include a communications subsystem **630**, which can include without limitation a modem, a network card (wireless or wired), an infra-red communication device, a wireless communication device and/or chipset (such as a Bluetooth™ device, an 802.11 device, a WiFi device, a WiMax device, a WWAN device, cellular communication facilities, etc.), and/or the like. The communications subsystem **630** may permit data to be exchanged with a network (such as the network described below, to name one example), with other computer systems, and/or with any other devices described herein. In many embodiments, the computer system **600** will further comprise a working memory **635**, which can include a RAM or ROM device, as described above.

The computer system **600** also may comprise software elements, shown as being currently located within the working memory **635**, including an operating system **640**, device drivers, executable libraries, and/or other code, such as one or more application programs **645**, which may comprise computer programs provided by various embodiments, and/or may be designed to implement methods, and/or configure systems, provided by other embodiments, as described

herein. Merely by way of example, one or more procedures described with respect to the method(s) discussed above might be implemented as code and/or instructions executable by a computer (and/or a processor within a computer); in an aspect, then, such code and/or instructions can be used to configure and/or adapt a general purpose computer (or other device) to perform one or more operations in accordance with the described methods.

A set of these instructions and/or code might be encoded and/or stored on a non-transitory computer readable storage medium, such as the storage device(s) **625** described above. In some cases, the storage medium might be incorporated within a computer system, such as the system **600**. In other embodiments, the storage medium might be separate from a computer system (i.e., a removable medium, such as a compact disc, etc.), and/or provided in an installation package, such that the storage medium can be used to program, configure and/or adapt a general purpose computer with the instructions/code stored thereon. These instructions might take the form of executable code, which is executable by the computer system **600** and/or might take the form of source and/or installable code, which, upon compilation and/or installation on the computer system **600** (e.g., using any of a variety of generally available compilers, installation programs, compression/decompression utilities, etc.) then takes the form of executable code.

It will be apparent to those skilled in the art that substantial variations may be made in accordance with specific requirements. For example, customized hardware (such as programmable logic controllers, field-programmable gate arrays, application-specific integrated circuits, and/or the like) might also be used, and/or particular elements might be implemented in hardware, software (including portable software, such as applets, etc.), or both. Further, connection to other computing devices such as network input/output devices may be employed.

As mentioned above, in one aspect, some embodiments may employ a computer system (such as the computer system **600**) to perform methods in accordance with various embodiments of the invention. According to a set of embodiments, some or all of the procedures of such methods are performed by the computer system **600** in response to processor **610** executing one or more sequences of one or more instructions (which might be incorporated into the operating system **640** and/or other code, such as an application program **645**) contained in the working memory **635**. Such instructions may be read into the working memory **635** from another computer readable medium, such as one or more of the storage device(s) **625**. Merely by way of example, execution of the sequences of instructions contained in the working memory **635** might cause the processor(s) **610** to perform one or more procedures of the methods described herein.

The terms "machine readable medium" and "computer readable medium," as used herein, refer to any medium that participates in providing data that causes a machine to operation in a specific fashion. In an embodiment implemented using the computer system **600**, various computer readable media might be involved in providing instructions/code to processor(s) **610** for execution and/or might be used to store and/or carry such instructions/code (e.g., as signals). In many implementations, a computer readable medium is a non-transitory, physical and/or tangible storage medium. Such a medium may take many forms, including but not limited to, non-volatile media, volatile media, and transmission media. Non-volatile media includes, for example, optical and/or magnetic disks, such as the storage device(s) **625**. Volatile media includes, without limitation, dynamic memory, such as

the working memory **635**. Transmission media includes, without limitation, coaxial cables, copper wire and fiber optics, including the wires that comprise the bus **605**, as well as the various components of the communication subsystem **630** (and/or the media by which the communications subsystem **630** provides communication with other devices). Hence, transmission media can also take the form of waves (including without limitation radio, acoustic and/or light waves, such as those generated during radio-wave and infrared data communications).

Common forms of physical and/or tangible computer readable media include, for example, a floppy disk, a flexible disk, a hard disk, magnetic tape, or any other magnetic medium, a CD-ROM, any other optical medium, a RAM, a PROM, and EPROM, a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code.

Various forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to the processor(s) **610** for execution. Merely by way of example, the instructions may initially be carried on a magnetic disk and/or optical disc of a remote computer. A remote computer might load the instructions into its dynamic memory and send the instructions as signals over a transmission medium to be received and/or executed by the computer system **600**. These signals, which might be in the form of electromagnetic signals, acoustic signals, optical signals and/or the like, are all examples of carrier waves on which instructions can be encoded, in accordance with various embodiments of the invention.

The communications subsystem **630** (and/or components thereof) generally will receive the signals, and the bus **605** then might carry the signals (and/or the data, instructions, etc. carried by the signals) to the working memory **635**, from which the processor(s) **605** retrieves and executes the instructions. The instructions received by the working memory **635** may optionally be stored on a storage device **625** either before or after execution by the processor(s) **610**.

While certain features and aspects have been described with respect to exemplary embodiments, one skilled in the art will recognize that numerous modifications are possible. For example, while embodiments are described above with regard to pavers and motor graders, it will be appreciated that the concepts presented here apply equally to a wide variety of heavy and construction equipment, including without limitation any type of equipment that removes or places construction material to high accuracy, such as milling machines, concrete paving machines, slip-form paving machines, and the like. Further, the methods and processes described herein may be implemented using hardware components, software components, and/or any combination thereof. Further, while various methods and processes described herein may be described with respect to particular structural and/or functional components for ease of description, methods provided by various embodiments are not limited to any particular structural and/or functional architecture but instead can be implemented on any suitable hardware, firmware and/or software configuration. Similarly, while certain functionality is ascribed to certain system components, unless the context dictates otherwise, this functionality can be distributed among various other system components in accordance with the several embodiments.

Moreover, while the procedures of the methods and processes described herein are described in a particular order for ease of description, unless the context dictates otherwise, various procedures may be reordered, added, and/or omitted in accordance with various embodiments. Moreover, the procedures described with respect to one method or process may be incorporated within other described methods or processes; likewise, system components described according to a particular structural architecture and/or with respect to one system may be organized in alternative structural architectures and/or incorporated within other described systems. Hence, while various embodiments are described with—or without—certain features for ease of description and to illustrate exemplary aspects of those embodiments, the various components and/or features described herein with respect to a particular embodiment can be substituted, added and/or subtracted from among other described embodiments, unless the context dictates otherwise. Consequently, although several exemplary embodiments are described above, it will be appreciated that the invention is intended to cover all modifications and equivalents within the scope of the following claims.

What is claimed is:

1. A road-forming machine, comprising:
   a locomotion system configured to move the road-forming machine;
   a road-forming system configured to form a road surface continuously as the road-forming machine moves;
   a communication interface to provide communication with a plurality of position measurement devices; and
   a control system comprising a processor, a non-transitory storage medium, and a set of instructions executable by the processor, the set of instructions comprising:
      instructions to receive position data from two or more position measurement devices, including a first position measurement device and a second position measurement device;
      instructions to control operation of the road-forming system based on determined positions of the road-forming system and a model stored on the non-transitory storage medium;
      instructions to determine a first position of the road-forming system based on position data received from the first position measurement device;
      instructions to transition from the first position measurement device to the second position measurement device without interrupting movement of the road-forming machine or formation of the road surface and without introducing a discontinuity in the formed road surface greater than a specified threshold value; and
      instructions to determine a second position of the road-forming system based on position data received from the second position measurement device.

2. The road-forming machine of claim **1**, wherein the set of instructions further comprises instructions to provide a user interface for the control system.

3. The road-forming machine of claim **2**, wherein the set of instructions further comprises instructions to display, on the user interface, information about the two or more position measurement devices.

4. The road-forming machine of claim **3**, wherein the information about the two or more position measurement devices comprises a distance to each of the two or more position measurement devices.

5. The road-forming machine of claim **3**, wherein the information about the two or more position measurement devices comprises a location of each of the two or more position measurement devices.

6. The road-forming machine of claim **3**, wherein the information about the two or more position measurement devices

indicates which of the two or more position measurement devices are providing position data used to determine a current position of the road-forming system.

7. The road-forming machine of claim 3, wherein the set of instructions further comprises instructions to receive, through the user interface, input indicating which of the two or more position measurement devices should be used to determine a current position of the road-forming system.

8. The road-forming machine of claim 2, wherein the set of instructions further comprises instructions to receive, through the user interface, input specifying the threshold value.

9. The road-forming machine of claim 8, wherein the input specifies a horizontal threshold.

10. The road-forming machine of claim 8, wherein the input specifies a vertical threshold.

11. The road-forming machine of claim 8, wherein the input specifies a distance threshold that defines a linear distance over which any discontinuity is absorbed.

12. The road-forming machine of claim 1, wherein the set of instructions comprises instructions to select one or more of the two or more position measurement devices from which to receive position data.

13. The road-forming machine of claim 1, wherein the road-forming machine is a paving machine.

14. The road-forming machine of claim 13, wherein forming a road surface comprises depositing paving material to form the road surface.

15. The road-forming machine of claim 13, wherein forming a road surface comprises extruding paving material to form the road surface.

16. The road-forming machine of claim 13, wherein the road-forming system comprises a plurality of legs, and wherein controlling operation of the road-forming system comprises controlling a height of one or more of the legs.

17. The road-forming machine of claim 16, wherein the set of instructions further comprises instructions to receive, through a user interface, input to manually modify a height of one or more of the legs.

18. The road-forming machine of claim 13, wherein the locomotion system comprises a plurality of tracks, and wherein controlling operation of the locomotion system comprises controlling steering of one or more of the tracks.

19. The road-forming machine of claim 18, wherein the set of instructions further comprises instructions to receive, through a user interface, input to manually modify a steering of one or more of the tracks.

20. The road-forming machine of claim 1, wherein the road-forming machine is a motor grader, and wherein forming the road surface comprises moving or removing material to form an underbed of the road surface.

21. The road-forming machine of claim 20, wherein controlling operation of the road-forming system comprises controlling a position of a blade of the motor grader.

22. The road-forming machine of claim 1, wherein forming the road surface comprises removing material from the road surface.

23. The road-forming machine of claim 1, wherein the set of instructions further comprises instructions to control operation of the locomotion system.

24. A control system for a road-forming machine, the control system, comprising:

one or more processors; and

a non-transitory computer readable medium in communication with the one or more processors, the computer readable medium having encoded thereon a set of instructions executable by the computer system to perform one or more operations, the set of instructions comprising:

instructions to receive position data from two or more position measurement devices, including a first position measurement device and a second position measurement device;

instructions to control operation of a locomotion system of the road-forming machine and a road-forming system of the road-forming machine to form a road surface continuously, based on determined positions of the road-forming system and a model stored on the non-transitory computer readable medium;

instructions to determine a first position of the road-forming system based on position data received from the first position measurement device;

instructions to transition from the first position measurement device to the second position measurement device without interrupting movement of the road-forming machine or formation of the road surface and without introducing a discontinuity in the road surface greater than a specified threshold value; and

instructions to determine a second position of the road-forming system based on position data received from the second position measurement device.

25. A method, comprising:

forming a road surface with a road-forming machine, the road-forming machine comprising:

a locomotion system configured to move the road-forming machine;

a road-forming system configured to form a road surface continually as the road-forming machine moves;

a communication interface to provide communication with a plurality of position measurement devices; and

a control system configured to control operation of the road-forming machine;

receiving, with the control system, position data from two or more position measurement devices, including a first position measurement device and a second position measurement device;

controlling, with the control system, operation of the locomotion system and the road-forming system based on determined positions of the road-forming system and a model stored on the non-transitory storage medium;

determining, with the control system, a first position of the road-forming system based on position data received from the first position measurement device;

transitioning, with the control system, from the first position measurement device to the second position measurement device without interrupting movement of the road-forming machine or formation of the road surface and without introducing a discontinuity in the formed road surface greater than a specified threshold value; and

determining a second position of the road-forming system based on position data received from the second position measurement device.

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